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Documentary evidence of past floods in Europe and their utility in flood frequency estimation

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Abstract

This review outlines the use of documentary evidence of historical flood events in contemporary flood frequency estimation in European countries. The study shows that despite widespread consensus in the scientific literature on the utility of documentary evidence, the actual migration from academic to practical application has been limited. A detailed review of flood frequency estimation guidelines from different countries showed that the value of historical data is generally recognised, but practical methods for systematic and routine inclusion of this type of data into risk analysis are in most cases not available. Studies of historical events were identified in most countries, and good examples of national databases attempting to collate the available information were identified. The conclusion is that there is considerable potential for improving the reliability of the current flood risk assessments by harvesting the valuable information on past extreme events contained in the historical data sets.

Keywords: flood frequency estimation, historical events, Europe,

1. Introduction

The reliable estimation of extreme flood events is challenging, but necessary for the design and operation of vital infrastructure such as flood defences, bridges, culverts and dams, and for more general flood risk management and

5 planning, e.g. emergency planning, flood risk mapping, and for defining
6 flood insurance premiums. In practice, this information is obtained using
7 flood frequency estimation techniques. Through statistical analysis of ob-
8 served events, a probabilistic behaviour of flood events is inferred which is
9 then extrapolated to provide estimates of the likely magnitude of future ex-
10 treme events (e.g. the magnitude of the flood expected to be exceeded on
11 average once every 100-year is estimated from a 40-year record). By nature,
12 extreme flood events are rare and seldom observed locally and as a result
13 hydrologists have little chance of gathering an adequate sample of recorded
14 events to make confident predictions. This naturally raises the question of
15 how best to extrapolate to extreme events, when no or only short series
16 of recent events are available. As floods occur in almost all regions of the
17 world, reliable flood estimation is a generic and shared problem. In Europe,
18 the last couple of decades have witnessed a number of high-magnitude low-
19 frequency flood events (Kundzewicz et al., 2013), causing widespread damage
20 and destruction. But flooding in Europe is not a recent phenomenon, and
21 there are multiple accounts of damaging flood events across the continent
22 going back centuries (e.g., Glaser et al., 2004, 2010; Baptista et al., 2011).
23 While the occurrence of extreme floods is a shared problem across Europe
24 (and beyond), the lack of cross-boundary cooperation (national and regional)
25 has lead to individual countries investing in research programmes to develop
26 national procedures for flood frequency estimation. As a result, no standard-
27 ised European approach or guidelines to flood frequency estimation exist.
28 Where methods do exist they are often relatively simple and their ability
29 to accurately predict the effect of environmental change (e.g. urbanisation,

30 land-use change, river training and climate change) is unknown (Castellarin
31 et al., 2012; Madsen et al., 2012). Also, the problem of consistent estimates
32 of extreme floods for trans-boundary rivers is rarely considered (Pappen-
33 berger et al., 2012). The COST Action ES0901 *European procedures for*
34 *flood frequency estimation* represents a novel opportunity to develop closer
35 understanding of the methods of flood frequency employed across Europe.
36 The Action is undertaking a pan-European comparison and evaluation of
37 different methods available for flood frequency estimation under the various
38 climatologic and geographic conditions found across Europe, and different
39 levels of data availability. The availability of such procedures is crucial for
40 the formulation of robust flood risk management strategies as required by the
41 Directive of the European Parliament and of the Council on the Assessment
42 and Management of Flood Risks (2007/60/EC).

43 Currently, flood frequency is most commonly based on systematic instru-
44 mental data, collected from established networks of gauging stations oper-
45 ated and maintained by a variety of station authorities/bodies across Europe.
46 These gauging stations are of various forms and complexity depending on the
47 level of data accuracy required. A more detailed discussion of availability,
48 length and types of flood data records as well as procedures for flood fre-
49 quency estimation procedures used across Europe is provided by Castellarin
50 et al. (2012).

51 A well-known consequence of the extrapolation from short series is the
52 high level of uncertainty associated with estimates of design floods with large
53 return periods. For example, estimating the 100-year design flood peak from
54 a 24-year record Stedinger and Griffis (2011) reported a factor of 4-to-1 be-

55 tween the upper and lower bounds of the 90% confidence interval. Given that
 56 the average record length is typically in the range 20-40 years, hydrologists
 57 have attempted to reduce the uncertainty levels by either: i) bringing addi-
 58 tional gauged data from nearby and comparable catchments into the anal-
 59 ysis (e.g., Hosking and Wallis, 1997), or ii) extending the available records
 60 by bringing flood data from before the beginning of systematic flow record-
 61 ing into the analysis in the form of historical and palaeoflood data (Guo and
 62 Cunnane, 1991), or iii) using rainfall stochastic generators and rainfall-runoff
 63 models to constrain extreme flood assessment by rainfall information (e.g.,
 64 Paquet et al., 2013). The three methods all have merit, but only the second
 65 is the focus of this review.

66 Realising the importance and utility of long-term datasets, flood hydrol-
 67 ogists have increasingly turned their attention to historical flood information
 68 (Brázdil et al., 1999, 2006; Glaser et al., 2004; Böhm and Wetzel, 2006; Mac-
 69 donald, 2006; McEwen and Werritty, 2007; Glaser et al., 2010; Herget and
 70 Meurs, 2010; Kobold, 2011; Santos et al., 2011; Brázdil et al., 2012), and
 71 how best to incorporate documentary evidence of such historical floods into
 72 flood frequency estimation (e.g., Stedinger and Cohn, 1986; Williams and
 73 Archer, 2002; Benito et al., 2004; Gaume et al., 2010; Macdonald and Black,
 74 2010; Gaál et al., 2010). However, the application of non-instrumental data
 75 into flood risk analysis is not new, as is evident from already existing guid-
 76 ance documents such as the Flood Studies Report (FSR) (NERC, 1975) in
 77 the UK, a French handbook for flood risk assessment with historical data
 78 (Miquel, 1984), the guidelines for flood frequency estimation in Germany
 79 (DVWK, 1999), and the methodological guide to implement the Floods Di-

80 rective in Spain (MARM, 2011). For the purpose of this study we propose
81 three definitions are adopted for the broad classification of different types of
82 hydrological data.

- 83 • Instrumental: long records, where records have been kept using avail-
84 able technologies, e.g. gauging stations or stage-boards (c. 1850-
85 present)
- 86 • Documentary: data derived from sources which are intermittent e.g.
87 documentary descriptions or flood levels marked on bridges (c. AD
88 1000-present). Documentary evidence most often refers to historical
89 events that occurred decades, centuries or even millennia ago, but it
90 can also relate to more recent events in locations where no instrumental
91 data are available.
- 92 • Palaeoflood: flood signatures recorded within depositional sequences,
93 often sedimentary (channel cut-offs and lakes), though recent work has
94 also witnessed flood signatures retrieved through dendrochronological
95 approaches (Pleistocene present). As with documentary evidence, ge-
96 omorphological evidence can also refer to recent flood events.

97 Regarding the historical and palaeoflood data we can add the following def-
98 initions:

- 99 • Perception threshold: level or discharge above which contemporary
100 society considered the event sufficiently severe to record information
101 about it, e.g. epigraphic markings (Macdonald, 2006) or a written
102 account in news media or a specialist publication.

103 • Censored data: unmeasured floods known to have occurred above or
104 below the perception threshold, despite not knowing their exact magni-
105 tude. Several researchers have shown that just knowing that a flood ex-
106 ceeded a perception threshold can add significant value to the flood fre-
107 quency analysis (e.g., Stedinger and Cohn, 1986; Cohn and Stedinger,
108 1987; Payraastre et al., 2011)

109 An important complication when considering documentary and palaeoflood
110 data is the impact of a changing environment (i.e. changes in climate and
111 land-use, or river engineering works) on the characteristics of the flood series,
112 and how to include this impact in future predictions.

113 The importance of data for assessing both the hydrology and impact of
114 past events has been recognised as an integral part of flood risk management
115 by the EU Flood Directive. The information collected in the Preliminary
116 Flood Risk Assessment (PFRA) documents developed by the individual EU
117 Member States starts with readily available or easily derivable information,
118 such as records and studies on long term developments. Member States
119 describe flood events that occurred in the past, which had significant adverse
120 impacts, and for which the likelihood of similar future events is still relevant,
121 reporting the frequency or recurrence of these events. The likely impact
122 of climate change on the occurrence and impact of floods shall be taken
123 into account in the review of the PFRA. For this, information beyond the
124 instrumental records is acknowledged as being able to reduce the uncertainty
125 of the assessment.

126 A key part of the COST Action ES0901 is to improve understanding of the
127 barriers to new approaches to flood estimation. The results and discussions

presented in this paper are mainly based on responses from a questionnaire circulated among COST Action participants on the use of historical floods and documentary evidence in flood frequency estimation. Specifically, this paper will undertake, first, a review of the general challenges for the incorporation of documentary evidence within flood frequency estimation. The focus of this paper is not to address the issues of data sources and information, which have previously been examined in detail by others, such as Brázdil et al. (2006, 2012), but to examine the use and application of historical records and information in flood frequency analysis; specifically. Second, challenges with the application of historical information within a changing environment will be assessed. Then, a review of the use of historical information in flood frequency estimation across Europe is undertaken by examining the detailed questionnaire responses which represent the position and statements of the individual countries. Finally, the paper will conclude by considering the current barriers to further application and potential developments.

2. Challenges for broader application of historical information

As documentary evidence most often predates the installation of gauging stations, and is not directly supported by other instrumental sources (using a limnometric scale e.g. stageboards), it generally provides indirect information on peak flood discharge, often in the form of a water level marker (Figure 1), or information that a specific location had been flooded, damaged or destroyed, or that the water level had reached a level relative to a structure (e.g. it had reached the top of the doorframe).

Different quantitative methods have attempted to extract the information

152 contained in historical data using a variety of approaches. The most com-
 153 mon approach is to consider a perception threshold for a historical period
 154 or sub-period, with the assumption that each flood exceeding this threshold
 155 has been recorded (e.g. NERC, 1975). As the consequences are important,
 156 this can sometimes be aided by thresholds within the environment of known
 157 exceedance. An example is the flooding of the Lincolnshire Plains by the
 158 River Trent in Central England when a low lying moraine (Spalford Bank) is
 159 overtopped, which is known to occur at flows in excess of $1000 \text{ m}^3\text{s}^{-1}$ (Mac-
 160 donald, 2013). Having established the threshold, the number of exceedance
 161 events during a period can then be retrieved from historical records. A more
 162 detailed approach involves the use of hydraulic formulae (e.g. Manning equa-
 163 tion) or one or two dimensional hydraulic models (St Venant equations) to
 164 convert historical flood levels into historical discharges (Lang et al., 2004a).
 165 As shown by Neppel et al. (2010) it is important to ensure that the hy-
 166 draulic model calibrates with flood marks and rating curves (when available)
 167 and reassess the hydrological homogeneity of discharge estimates at several
 168 places. Hydraulic studies should provide a discharge estimate, but also a
 169 range of possible values within an interval, based on a sensitive analysis or
 170 an uncertainty analysis.

171 Several statistical approaches were developed in the past to improve the
 172 flood frequency curve estimation by extracting the information contained in
 173 the different types of historical records discussed above. In the USA, Bul-
 174 letin 17 B (USWRC, 1982) proposed the weighted moments (WM) technique
 175 for incorporating historical information in a flood frequency analysis. The
 176 WM technique is a straightforward method that is noticeable for ease of im-

177 plementation. Stedinger and Cohn (1986) developed a maximum likelihood
 178 estimator (MLE), which was more flexible, efficient and robust than the WM
 179 technique. Moreover, it allowed the introduction of binomial censored data
 180 into the likelihood function; however, MLEs present numerical problems in
 181 some occasions. To avoid this drawback, while maintaining the efficiency
 182 of MLE technique, the expected moments algorithm (EMA) was developed
 183 (Cohn et al., 1997). Reis and Stedinger (2005) proposed a Bayesian tech-
 184 nique based on Markov Chain Monte Carlo methods (BMCMC) that im-
 185 proves previous techniques by providing the full posterior distributions of
 186 flood quantiles. Likewise, the BMCMC technique allows for the introduction
 187 of uncertainty into historical peak discharge estimates. The WM technique
 188 was adapted to the case of probability weighted moments (PWM), to pro-
 189 duce the partial probability weighted moments (PPWM) approach (Wang,
 190 1990). The EMA technique was also adapted to the PWM case, providing
 191 the expected probability weighted moment (EPWM) estimator, which im-
 192 proves the estimation of the shape parameter, but has also shown some bias
 193 (Jeon et al., 2011).

194 An example of how the inclusion of historical events can help flood fre-
 195 quency estimation to better represent the probabilistic behaviour of flood
 196 events can be seen in Figure 2. It shows the results at the Tortosa gauging
 197 station located on the River Ebro in Spain, a comparison between two Gen-
 198 eralised Extreme Value (GEV) distributions fitted to i) a sample of 31 annual
 199 maximum flood peaks recorded at the gauging station (instrumental) by the
 200 method of L-moments, and ii) the same sample of instrumental events, but
 201 enhanced with seven historical flood events by the method of PPWM. From

202 the frequency plot in Figure 2 it is clear that the GEV distribution fitted to
203 the instrumental record only, would result in severe under-estimation of the
204 real flood risk at the site of interest. However, the inclusion of the histori-
205 cal records estimated from a set of flood marks recorded at a house close to
206 the reach improved the estimation of extreme return period floods, as their
207 magnitude was unknown from the short instrumental record.

208 Most of these analytical developments have been undertaken within the
209 academic field. However, extending these improvements to routine practical
210 use is not trivial, principally because of the mathematical complexity of most
211 techniques. For instance, classical MLEs are efficient for sufficiently long
212 records, but may produce numerical problems in application to case studies
213 when sample size is small (El Adlouni et al., 2007); a significant drawback for
214 recommending this technique for practical application. Bayesian techniques
215 also present critical steps, such as the estimation of prior distributions and
216 the computation of posterior distributions which are not always straightfor-
217 ward. The elegant statistical models based on censored data sources and
218 solved using likelihood functions, sometimes combined with Bayesian statis-
219 tics (Reis and Stedinger, 2005), can provide very good results. Nevertheless,
220 this review suggests that whilst these models exist, there is limited evidence
221 that they have migrated from the academic field into operational guidelines.
222 Potential barriers to the broader application of these approaches may reflect
223 the complex computational requirements and site specific characteristics that
224 may be best combined with specific methods, though the survey undertaken
225 in this study did not contain information on why certain approaches are not
226 applied. These problems lead to the use of the more simplistic, but robust,

227 methods in practice, as recommended by operational guidelines, such as the
228 WM technique in the United States and the PPWM in Spain.

229 In addition to providing formal input into quantitative flood frequency
230 estimation, documentary evidence of past events can be helpful in commu-
231 nicating flood risk to non-specialist stakeholders (McEwen et al., 2013) and
232 for better understanding variations in flood seasonality (Macdonald, 2012).
233 The transformation of information from descriptive accounts of past events
234 into more easily understood groups of flood magnitude has seen the use of
235 indices, often using a scale dividing the events into a set of qualitative classes
236 (Sturm et al., 2001; Llasat et al., 2005) for flood severity, see Brázdil et al.
237 (2006, 2012); for example class 1 (low to intermediate events: damage and
238 flooding are limited to restricted areas), class 2 (high events: flooded area
239 and debris flow are important, structures such as dikes and roads have been
240 destroyed for several hundred of meters), class 3 (extreme events: damage
241 or destruction of important structures and flooding on the whole plain). Al-
242 though a useful tool for categorising and visualising flood magnitude, this
243 approach has yet to be useful in the estimation of flood frequency, and is
244 unlikely to present any advances as the approach removes individual event
245 information and groups the events, thereby reducing the potential value of
246 the data.

247 **3. Assessment of environmental change**

248 There is some discussion provided as to means of accounting for the im-
249 pact of environmental change on flood occurrence, with several countries
250 undertaking comparison to nearby stations, for non-homogeneity and trend

251 studies. However, in a review of existing guidance in European countries
252 on how to include considerations of environmental change in flood frequency
253 estimation, Madsen et al. (2012) found that generally little or no guidance
254 is provided for how to deal with trend or non-homogeneity when identified,
255 and how this knowledge should be incorporated into flood estimation. This
256 is clearly an area where much more effort is required to translate scientific
257 research into operational guidelines.

258 Different types of non-stationarity can be considered within historical
259 records, as the frequency distribution could change during the period for
260 which historical and palaeoflood data are recorded: i) the changes related
261 to non-homogeneity problems (historical data availability, transformation of
262 indirect information to discharge estimate); ii) climatic variability over long
263 time scales could limit the utility of historical data under a stationarity frame-
264 work to some hundreds of years in the past (Hosking and Wallis, 1997). This
265 topic remains an open field of research, with present interest amplified by
266 the perspective of climate change for the 20th and 21st centuries; iii) chan-
267 nel changes (natural and anthropogenic) over long timeframes (e.g., Brázdil
268 et al., 2011a). As a means of minimising the potential impact of these cli-
269 matic non-homogeneities, historical records used for flood frequency analysis
270 are not extended back beyond around 400 years in Spain. This practice lim-
271 its the influence of past climatic changes; as a greater frequency of extreme
272 flood events are found in the period 1540-1640 (Benito et al., 2003). Similar
273 timeframes are recommended in a number of academic papers (e.g. Parent
274 and Bernier, 2003; Macdonald, 2013), but this often focuses on concerns re-
275 lating to data quality and quantity prior to this (as discussed above) rather

276 than climatic variability, with several studies commenting on the longer time-
277 frame providing greater climatic variability, and therefore a more uncertain
278 climate range (e.g. Macdonald et al., 2006). These issues become even more
279 important when attempting to merge gauged flow data with palaeoflood data
280 stretching back millennia, though it could be argued that climatic variabil-
281 ity over millennial timescales incorporates sufficient variability that climate
282 phases become less significant. While some researcher have embraced the use
283 of palaeoflood data (Baker et al., 2002), others remain more sceptical of their
284 practical utility, especially when regional flood frequency methods are avail-
285 able (e.g. Hosking and Wallis, 1986). Notably, Neppel et al. (2010) identified
286 large error associated with historical flood magnitude estimation could lead
287 to a reduction in the precision of design flood estimates when compared to
288 estimates using gauged data only, supporting the view that palaeoflood data
289 should be handled carefully when included into a flood frequency analysis.

290 Lang et al. (2004b) proposed a statistical test based on the Poisson process
291 for the detection of changes in peak-over-threshold series. It has been applied
292 to several historical series in France and Spain (Barriendos et al., 1999) and
293 in central Europe (Glaser et al., 2004). The power of the test is limited when
294 the number of historical floods is low. On the contrary, including low to
295 intermediate historical floods increases the risk of non-homogeneity, as such
296 floods can be strongly influenced by anthropogenic changes. It is therefore
297 recommended to check the validity of the rating curves used for historical
298 floods.

299 The development of slackwater deposits as a tool in the reconstruction of
300 palaeoflood series has expanded extensively over the last couple of decades

301 Werritty et al. (2006); Jones et al. (2010); Huang et al. (2012); Dezileau et al.
302 (2014), with a number of review papers (e.g. Benito and Thorndycraft, 2006)
303 and books (Gregory and Benito, 2003) addressing the topic in detail.

304 Lakes can act as efficient repositories for sediments eroded from within the
305 catchment and that are transported through the fluvial system (Mackereth,
306 1966). The sediments reaching a lake are dependent on a number of variables
307 which may vary through time and space; see Schillereff et al. (2014) for a
308 full review. The sediments that reach the lake may be laid down providing a
309 sedimentary record of high-magnitude flows which appear as distinct lamina-
310 tions of coarse material. An increasing number of studies have examined lake
311 sediment sequences with the intention of determining flood histories (Noren
312 et al., 2002; Gilli et al., 2013; Wilhelm et al., 2013). The sediments preserved
313 within the lake can contribute valuable information on flood frequency and
314 potential magnitude of single events over timeframes reaching several mil-
315 lennia (Noren et al., 2002). For example, Swierczynski et al. (2013) derived
316 a 7,000-year flood chronology for the lake Mondsee in Upper Austria. Even
317 the seasons of the palaeofloods could be precisely determined by the micro-
318 stratigraphic position of a detrital layer within the annual succession of lake
319 deposition. This flood chronology shows a striking variability in the flood
320 occurrence from decadal to millennial time scales. There is a period of more
321 than 200 years (21 B.C. 216 A.D.) without any flood documented, whereas
322 the average frequency is 0.04 floods/year yielding 9 floods for such a time
323 interval.

324 4. Questionnaire on use of historical data in flood frequency esti- 325 mation

326 As part of the COST Action ES0901 *European procedures for flood fre-*
327 *quency estimation* a review was undertaken examining if, and how different
328 European countries incorporate historical information into flood frequency
329 analysis. Responses were collected from 15 European countries, represent-
330 ing the different participant countries of the COST Action; all participant
331 countries were invited to contribute through the completion of a question-
332 naire, which was initially distributed to COST participants, who completed
333 or passed onto colleagues better placed to do so. The questionnaire applied
334 the definitions detailed above so as to distinguish between historical and in-
335 strumental data series. A summary version of the questionnaire responses is
336 provided in Table 1.

337 TABLE 1

338 The following three sub-sections summarise the information collected
339 from the questionnaires. In particular: i) the length of existing historical
340 data series, ii) the accessibility to historical flood data, and iii) summaries of
341 specific guidelines developed in European countries.

342 4.1. Data availability

343 Each country was asked to provide details of the sites and locations where
344 the most complete historical series are available. This information is used to
345 provide an indication of the types and use of historical records as a series of
346 national summaries, but cannot be considered as an exhaustive inventory.

347 For each reported case-study the ratio between the length of the instru-

348 mental record and the total time from the end of the instrumental record
349 until the first recorded historical flood event was calculated. The average of
350 the ratios calculated from the case studies within each country are reported
351 (Table 2) together with the number of case-studies and the oldest recorded
352 flood event. Note that the oldest flood refers to the oldest flood event as-
353 sociated with an estimate of peak flow; in some countries, older events were
354 recorded but could not be assigned an estimate of the discharge.

355 TABLE 2

356 The average ratios are all below 0.50 suggesting that additional infor-
357 mation of extreme floods can be found as far back in time as twice the
358 period covered by the instrumental record. The countries listed in Table 2
359 are representative of North, South, East and West Europe, indicating that
360 historically augmented flood estimation could be useful across the continent.
361 While no quantitative assessment of the benefit of the extended data series
362 were conducted as part of this review, several previous studies have high-
363 lighted the utility of such series. For example, Macdonald et al. (2013) found
364 that extending a 40-year instrumental record with documentary evidence of
365 flooding dating back to 1772 resulted in an almost 50% reduction on the
366 uncertainty of the estimated design flood with a return period of 100 years.
367 Similar conclusions have been reached by other researchers such as Payrastre
368 et al. (2011). Thus, the data series listed in Table 2 represent an important
369 resource for providing more reliable estimates of flood risk across Europe.

370 4.2. Central depository of historical data

371 No centralised database exists as a depository for flood information at
372 a European scale. But a variety of laudable national/regional/local and

individual databases exists. However, there is no common agreed format, and the databases often include either/or both qualitative and quantitative information with limited quality control on the information uploaded. The purpose of existing data varies, which often reflects the structure and types of information collected, the result is that some disciplines may feel insufficient or 'the wrong' type of data may be present, reflecting the varied uses of historical information, from those examining social impacts of past floods to those interested in using the information in flood frequency estimates, as such some disciplines may consider important information to be absent. These databases tend to be funded through a variety of different mechanisms, with few receiving continuous central support; as such they are funded initially, but then become reliant on individuals or professional societies for continuation, good examples being the British Hydrological Society Chronology for British Hydrology Events (BHS CBHE), as described by Black and Law (2004), or the French national Historical Database BDHI currently in development in the framework of the EU Flood Directive (Lang et al., 2012). Whilst a valuable resource the full potential of these databases cannot be realised in pan-European flood frequency estimation at present, due to the absence of a standardised method for construction and minimum data requirements. The National Disaster Archive compiled by the Disaster & Emergency Management Presidency (AFAD) in Turkey, for example, provides tabular and spatial information (date, location) about the entire spectrum of historic disaster events (e.g., floods, droughts, earthquakes, landslides, forest fires, nuclear accidents, etc.) associated with figures of deaths, injuries, affected populations, etc. However, this is not immediately utilizable

398 in flood frequency analyses due to the lack of data describing the physical
399 characteristics of the events, such as flood levels and discharges.

400 Recent efforts by a group of researchers from the Slovak Academy of
401 Sciences started with mapping of all historical flood marks and collecting
402 historical reports of floods in Slovakia. Their results are continuously pub-
403 lished, e.g. recent studies by Pekárová et al. (2011, 2013) give the overview of
404 the history of floods and extreme events in Slovakia and in the upper Danube
405 River Basin at Bratislava.

406 These databases provide pockets of knowledge, but large areas of Europe
407 remain ungauged. The use of geospatial databases for the visualisation of in-
408 formation and capability to embed images within such databases presents an
409 important development, permitting flood levels and additional information
410 beyond a basic descriptive account to be housed within each flood account,
411 empowering the researcher to more rapidly and easily access required infor-
412 mation. One of the principal constraints to the wider application of histor-
413 ical information in flood frequency analysis has been the time requirements
414 for collecting the necessary data; well developed and constructed geospatial
415 databases present a valuable step towards removing these constraints.

416 *4.3. Practical guidelines for inclusion of historical data*

417 A number of countries were identified as possessing practical guidelines
418 for inclusion of historical flood information into flood frequency estimation,
419 including: Austria, France, Germany, Ireland, Italy, Slovakia, Spain and the
420 United Kingdom.

421

422 **Austria**

423 In Austria historical information, where available, was included in the devel-
424 opment of national maps of flood discharge (Merz et al., 2008). The historical
425 information was included in flood frequency estimation procedure based on
426 the use of likelihood functions of censored information and Bayesian mod-
427 elling techniques as described by Merz and Blöschl (2008) and Viglione et al.
428 (2013).

429

430 **France**

431 Miquel (1984) presented a methodological guide for the inclusion of histori-
432 cal data in flood frequency analysis. It was based on a Bayesian approach to
433 peak-over-threshold (POT) values with an a posteriori estimate of the flood
434 distribution, by combining with the Bayes theorem and a priori distribution
435 based on instrumental data and historical POT values. Parent and Bernier
436 (2003) presented an application of this model, using a MCMC algorithm for
437 computation. Naulet et al. (2005) used a maximum likelihood approach on
438 annual maximum values, with different sub-periods (each one being related
439 to a threshold of perception according to documentary sources availability)
440 and different types of data (censored, censored with uncertainties, binomial
441 censored). Lang et al. (2010) and Neppel et al. (2010) applied an error
442 model on discharge estimate, accounting for random errors (sampling uncer-
443 tainties) and systematic errors (water level and rating curve errors). They
444 showed that ignoring the rating curve errors may lead to an unduly optimistic
445 reduction in the final uncertainty in estimation of flood discharge distribu-
446 tion. Gaume et al. (2010) and Payraastre et al. (2011) presented a Bayesian
447 framework allowing the use of regional information of historical floods at un-

448 gauged sites. They also provided results on the usefulness of historical data
449 in flood frequency analysis regarding the type of data (censored, censored
450 with uncertainties, binomial censored).

451

452 **Germany**

453 The German Association for Water, Wastewater and Waste (DWA) and its
454 predecessor DVWK have published guidelines which give recommendations
455 for the use of historical sources and data: DWA (2008): Guidelines on how
456 to exploit and interpret historical sources for determining extreme flood dis-
457 charges. DVWK (1999): Guidelines for integrating large historical flood
458 magnitudes in flood frequency analysis are based on the methods presented
459 in Bulletin 17B (USWRC, 1982). This publication was superseded by the
460 more recent guidelines on flood estimation which devotes a separate chap-
461 ter to the integration of large historical flood magnitudes in flood frequency
462 analysis (DWA, 2012). Three alternative approaches are offered to consider
463 historical data in the parameter estimation of the frequency distribution.
464 One of them is based on the definition of a set of likelihood functions repre-
465 senting the actual nature of the available flood information, i.e.: i) discharge
466 of historical information known, ii) discharge is known to fall within an inter-
467 val (upper and lower bound specified), or iii) event is known to have exceed
468 a perception threshold, but the actual discharge value is unknown.

469

470 **Ireland**

471 In Ireland, the generally accepted approach to incorporating historical flood
472 data follows that put forward by Bayliss and Reed (2001) in a similar man-

ner to that described for the UK. With the imminent release of the Flood Studies Update (FSU) methodologies in 2014, growth curve analysis will use L-moment methods to derive growth curves, with the EV1 and LN2 distributions being the preferred distributions for use at gauged locations. It is envisaged that methods of incorporating historical information will move towards the use of L-moment based methods in the future. The central source of information on historical floods will remain the Irish flood hazard mapping website, floodmaps.ie.

Italy

The gauging network for systematic river-stage monitoring in Italy was largely installed in the twentieth century, therefore Italian streamflow records are usually much shorter than 100 years (Calenda et al., 2009). In this context, historical and non-systematic information on flood events is a valuable resource. Historical evidence of flooding in Italy has been recorded (e.g., Aldrete, 2007), and national databases of historical disasters (mainly landslides and floods) have been established (Guzzetti et al., 1996, 2004). Nevertheless, these databases contain predominantly descriptive information such as: triggering mechanisms, economic losses and casualties, but little information related to peak discharge. Consequently, although basin authorities routinely use information on historical floods for geographically delineating the most vulnerable areas and acknowledge the value of this information for improving flood frequency estimation (see e.g., AdB-Po, 1999), no evidence of practical use of historical floods in flood frequency estimation was identified in Italy at a national level, though examples were found at regional and local scales.

498 For example an application to the Piedmont region reported by Claps and
499 Laio (2008) and Laio et al. (2011), and local application by Calenda et al.
500 (2009) on the River Tiber.

501

502 **Czech and Slovak Republics**

503 There are several methods for inclusion of historical flood data in flood fre-
504 quency estimation in the Czech and Slovak Republics, which were published
505 in reports e.g. Dub and Nemec (1969), Kašpárek (1984) and Novický et al.
506 (1992). These methods are based on corrections of systematic errors by
507 estimation of statistical parameters (coefficient of variability, skewness) of
508 applied distribution functions. The German guidelines for using historical
509 floods, published in DVWK (1999), was applied by Szolgay et al. (2008).
510 Recent studies in Slovakia used a Bayesian framework to include both local
511 and regional information about historical floods at ungauged sites, and to
512 provide results on the usefulness of different types of historical data in flood
513 frequency analysis (Gaál et al., 2010, 2013).

514 Flood frequency analysis in the Czech Republic is based on combina-
515 tion of floods derived from documentary evidence and systematic hydrologic
516 measurements, which permits the creation of 500-year series: examples in-
517 clude the Vltava (Prague), Ohře (Louny) and Elbe (Děčín) series in Bohemia
518 (Brázdil et al., 2005). In Moravia (eastern Czech Republic), similar compiled
519 series are available for the River Morava, starting as early as 1691 (Brázdil
520 et al., 2011b). More recently, knowledge of historical floods coupled with
521 flood plain information in Prague was used for the estimation of hydraulic
522 parameters, permitting the calculation of peak discharges of past disastrous

523 floods during the pre-instrumental period (Elleder et al., 2013).

524

525 **Spain**

526 In Spain, the use of historical records is generally recommended when pos-
527 sible, by fitting a GEV distribution by the PPWM method. In addition,
528 historical records were used in some Mediterranean basins (3) to improve:
529 i) the results of the regional flood frequency analysis, and ii) estimates of
530 high return period quantiles along the Mediterranean East coast of Spain
531 (Jiménez-Álvarez et al., 2012).

532 The 92nd Region is located in the northeast of Spain, including the rivers
533 of the left bank of the River Ebro with heads in the central Pyrenees (Figure
534 3). In this region the regional coefficient of skewness (L-CS) estimated from
535 instrumental records was improved by the use of historical information. It
536 was seen that two high flood events that occurred in the 20th century affected
537 most of this region (1907 and 1982). However, they were not recorded, as the
538 former occurred before the existence of a gauging station network in Spain,
539 while the latter exceeded the maximum capacity of the gauging stations.
540 Values of at-site L-CS were improved by the use of a GEV distribution fitted
541 with historical information by the PPWM method. The regional L-CS value
542 was updated by a weighted mean of at-site L-CS with weighting factors
543 dependent on the uncertainty of at-site estimations.

544 The 72nd and 82nd regions are located in the eastern part of Spain, in-
545 cluding the lower parts of the Júcar and Segura catchments that are affected
546 by rare and heavy rainfall events coming from the Mediterranean Sea (Figure
547 3). These events are caused by cut-off lows occurring in spring and autumn,

when cold air in the upper part of the troposphere moves from northern latitudes to the south over the warm Mediterranean Sea, generating heavy convective rainfall events and, consequently, intense flood events. However, there is a lack of information recorded about these flood events; either they occurred in the past before a gauging station was installed, or they were not recorded, as they exceeded gauging station capacity. This lack of information can result in potentially severe underestimation of higher return period quantiles. Estimates with only instrumental records can lead to magnitudes around 5 to 10 times smaller for the 500-year return period. As floods come from two types of rainfall events, a Two-Component Extreme Value (TCEV) distribution (Rossi et al., 1984) fitted by MLE is recommended. In these regions, the use of historical information in flood frequency is crucial to achieve reliable estimation of higher return period quantiles. In Spain, the use of historical information to improve flood frequency analyses is recommended (MARM, 2011). A large catalogue of historical floods is supplied by the Spanish civil defence organization.

United Kingdom

The use of historical record has been called for since the mid-1970s, initially through the early work of the Flood Studies Report (NERC, 1975) and Potter (1978). More recently, Bayliss and Reed (2001) provided the first approach designed specifically for practitioners on how to augment instrumental datasets with documental evidence of historical records. However, the uptake of this approach has been piecemeal and slow, in part as practitioners still require a user-friendly tool for incorporating historical data into

573 flood frequency analysis. Current methods widely employed for incorporating
574 historical flood information into flood assessments often consist of a conven-
575 tional flood frequency plot, with the historical levels/discharges marked on,
576 but importantly not included within the statistical analysis. The use of an
577 informal graphical plotting approach was advocated by Reed and Robson
578 (1999) to permit greater confidence among practitioners in the application
579 of historical data. By contrast, Macdonald et al. (2006) and Macdonald
580 and Black (2010) have advocated the use of L-Moments, as they permit
581 greater flexibility and retained an approach practitioners were already fa-
582 miliar with in dealing with pooled data, compared to more mathematically
583 involved Maximum-Likelihood approaches (Macdonald et al., 2013). Each of
584 the approaches considered a preference for a Generalised Logistic distribution
585 model to represent the flood growth curve. An interesting use of historical
586 information was reported by Williams and Archer (2002) who used historical
587 flood data to assess the return period of a recent large event.

588 **5. Discussion**

589 Despite general agreement in the scientific literature on the utility of
590 historical flood information in flood frequency estimation, the survey un-
591 dertaken has shown that there is only a limited transfer of methods from
592 academia into practical guidance. A few good examples of guidelines and
593 depositories for historical flood data were identified, but no single unified
594 approach or database is evident. Depositories were identified both as part
595 of larger government hydrometric databases, but also existing independently
596 from official government databases, and operated mainly by volunteers and

597 populated by citizen science efforts (e.g. UK BHS CBHE). The lack of prac-
 598 tical guidelines and fragmented access to historical information are practical
 599 barriers towards more operational use of these data sources to support cur-
 600 rent risk mapping efforts and decision-making problems. In addition, it is
 601 also clear that the inclusion of historical information is not always straight-
 602 forward, requiring a greater degree of scrutiny before application than typ-
 603 ically required for instrumental data. In particular, it should be recognised
 604 that historical information is fundamentally different from quality controlled
 605 streamflow measurements obtained from gauging stations. For example, the
 606 degree of certainty associated with discharge estimates from historical in-
 607 formation requires special consideration. Research has shown that simply
 608 ignoring uncertainties on discharge estimates will favour the use of histori-
 609 cal information, as sampling uncertainty is reduced by increasing the length
 610 of the flood period. Nevertheless, it is important to correctly describe the
 611 uncertainties on peak discharge for the instrumental, historical and palae-
 612 oflood data, including errors on water level H , on the rating curve $Q(H)$,
 613 on the threshold of perception and on the starting date of the historical pe-
 614 riod. The latter should not be systematically the date of the oldest flood
 615 in the historical data set (Strupczewski et al., 2013), but should include a
 616 period prior to this. The Bayesian framework appears to be a suitable sta-
 617 tistical tool, enabling inclusion of several kinds of data (e.g. single values,
 618 intervals, number of exceedances) and able to include errors/uncertainties on
 619 discharge estimates (i.e., systematic error on water levels and on the rating
 620 curve transformation) into flood frequency analysis.

621 While this review has found that there is largely consensus in the sci-

entific literature as to the usefulness of historical data in flood frequency estimation, the methods have overwhelmingly focussed on extending at-site estimates. Few studies have reported on the use of historical information in a regional context. A notable exception is the procedure for certain geographical regions of Spain, where the occurrence of very extreme events in the past has resulted in a set of regional flood frequency curves adjusted upwards to represent the worst case, even if no actual events has been observed at a particular site. This is potentially a very interesting methodological development, recognising the limitations of fitting current statistical models to datasets that are known not to include potentially very extreme events, similar to events that have occurred in other locations within the region. By contrast, Hosking and Wallis (1997) argue that historical information is of limited use in regional flood frequency estimation; their reservations are based on i) concerns about the accuracy and completeness of the historical information (historical data are most often found in old and large human settlements and not at a representative sample across all possible catchments), ii) representativeness of catchment within a region where historical data are available, and iii) using data so far in the past that the underlying frequency distribution might have changed too much (non-stationarity). A regional model combining both regional and historical data was presented by Jin and Stedinger (1989) combining the index flood method with a GEV distribution where the model parameters are estimated using a combination of probability weighted moments and a maximum likelihood procedure. Gaume et al. (2010) also presented a maximum-likelihood approach to combining regional and historical data within the framework of the index flood method. Sur-

647 prisingly, no or only little further development of these procedures appears
648 to have been reported in the literature, but this is an area where further re-
649 search is still required to develop a new generation of risk tools to effectively
650 allow regional models to use historical information, and to define procedures
651 to enable the transfer of historical data between catchments.

652 The potential of historical information in public awareness of flood risk is
653 considerable, historical events are tangible, with epigraphic markings provid-
654 ing an example of how communities have preserved evidence from past events
655 to educate future generations of flood risk, which may not be witnessed within
656 any single lifetime. Increasingly recognition of the non-quantitative informa-
657 tion contained within historical flood accounts is being recognised, providing
658 detailed descriptions of the social and cultural responses to extreme events,
659 responses that inherently shape current flood risk management approaches
660 through *learned knowledge* within communities. This informal knowledge
661 is increasingly being sought and embedded within local flood risk manage-
662 ment plans, as recognition of the value of local lay knowledge has developed
663 (McEwen et al., 2013).

664 The development of national approaches in individual countries has re-
665 sulted in no-single approach being applied at a European level, constraining
666 the potential for cross border information transfer, and at worst leading to
667 misunderstanding and poor communication to the public (e.g. flood maps
668 with different flood extents at the boundary). Future research must address
669 several key themes:

- 670 • construction of a single database framework within which data can
671 be stored and managed, with both extraction, uploading (preferably

672 through approaches advocated by citizen science) and geospatial pre-
673 sentation capabilities;

674 • move towards organisation data sharing across boundaries, with greater
675 free access to data for benchmark sites;

676 • development of a computationally simple user interface toolbox, within
677 which hydrological series comprising of different data types, lengths and
678 completeness can be assessed together;

679 • development of a set of practices for the treatment of data uncertainty
680 associated with historical records; and,

681 • a forum for the sharing and review of best practice at a European level.

682 Inevitably an assessment of the data has to be made by the individual under-
683 taking the analysis and the purpose for which the data is compiled, but the
684 above proposals would facilitate a more rapid and structured approach to the
685 compilation and analysis of the data, overcoming a number of the obstacles
686 currently cited as prohibiting expansion in the application of historical data.

687 **6. Conclusions**

688 There is increasing recognition that historical records of flooding provide
689 a valuable means by which extreme rare events can be better understood,
690 facilitating more enlightened flood frequency analysis where interest is fo-
691 cused on extreme events (events with a return period in excess of 100 years).
692 As evidenced within this research (Table 1 and 2), a number of examples of
693 historical flood analysis are present within most European countries, with

694 a number of countries if not actively incorporating historical flood records
695 into flood frequency analysis considering how they can be used, in compli-
696 ance with the EU Floods Directive (2007/60/EC). Whilst no single approach
697 is uniformly applied to historical flood frequency analysis across Europe, a
698 number of national and regional approaches exists. As historical evidence is
699 often found in connection with large rivers, the use of this information could
700 be a key driver in both academic and practical investigations of transbound-
701 ary flood management.

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Table 1: Use of historical data in flood frequency estimation.

Country	Routine use of historical flood data?	Existing recognised approach?	Preferred method	Information on catchment change?	Central depository of historical flood data?	Website
Austria	Yes	Yes	Bayesian methods	Yes	Yes	http://chyd.gv.at/
Czech Republic	No	No	-	No	No	
Finland	No	No	-	No	Yes	www.ymparisto.fi/oiva
France	Not routinely	No, but guidelines available	Bayesian methods	When available	Yes	http://www.reperesdecruis-seine.fr/carte.php
Germany	No, but some practical use reported	No but guidelines available	Maximum Likelihood	Not routinely	Yes	http://undine.bafg.de
Ireland	No	No	-	No	Yes	
Italy	Not routinely	No	-	No	Yes	http://webmap.irpi.cnr.it/
Norway	No	No	-	No	Yes	
Lithuania	No	No	-	No	No	
Poland	Not routinely	No but guidelines available	-	No	No	
Portugal	Not routinely	No	-	Yes	Yes	http://geo.suinh.pt/AtlasAgua/
Slovakia	No, but some practical use reported	Yes	MCMC techniques	No	No	
Slovenia	No	No	-	Not routinely	Yes	http://vode.arso.gov.si/hidrarhiv/pov_arhiv_tah.php
Spain	Yes	Yes	PPWM method	No	Yes	
Turkey	No	No but guidelines (DSI, 2012) exist	-	No	Yes	http://tuua.afad.gov.tr
United Kingdom	Not routinely	Guidance available	Graphical method	Not routinely	Yes	http://www.trp.dundee.ac.uk/cbhe/welcome.ht

Table 2: Summary of historical flood records. *Ratio* in column four refers to the average ratio between length of instrumental record and the total length of the historical plus instrumental records.

Country	No. studies	Year of	Ratio
		oldest recorded flood	
Czech Republic	8	1118	0.22
France	13	1601	0.23
Germany	1	1374	0.31
Lithuania	2	1427	0.33
Norway	12	1345	0.47
Slovakia	5	1012	0.24
Spain	11	1779	0.38
United Kingdom	14	1210	0.19

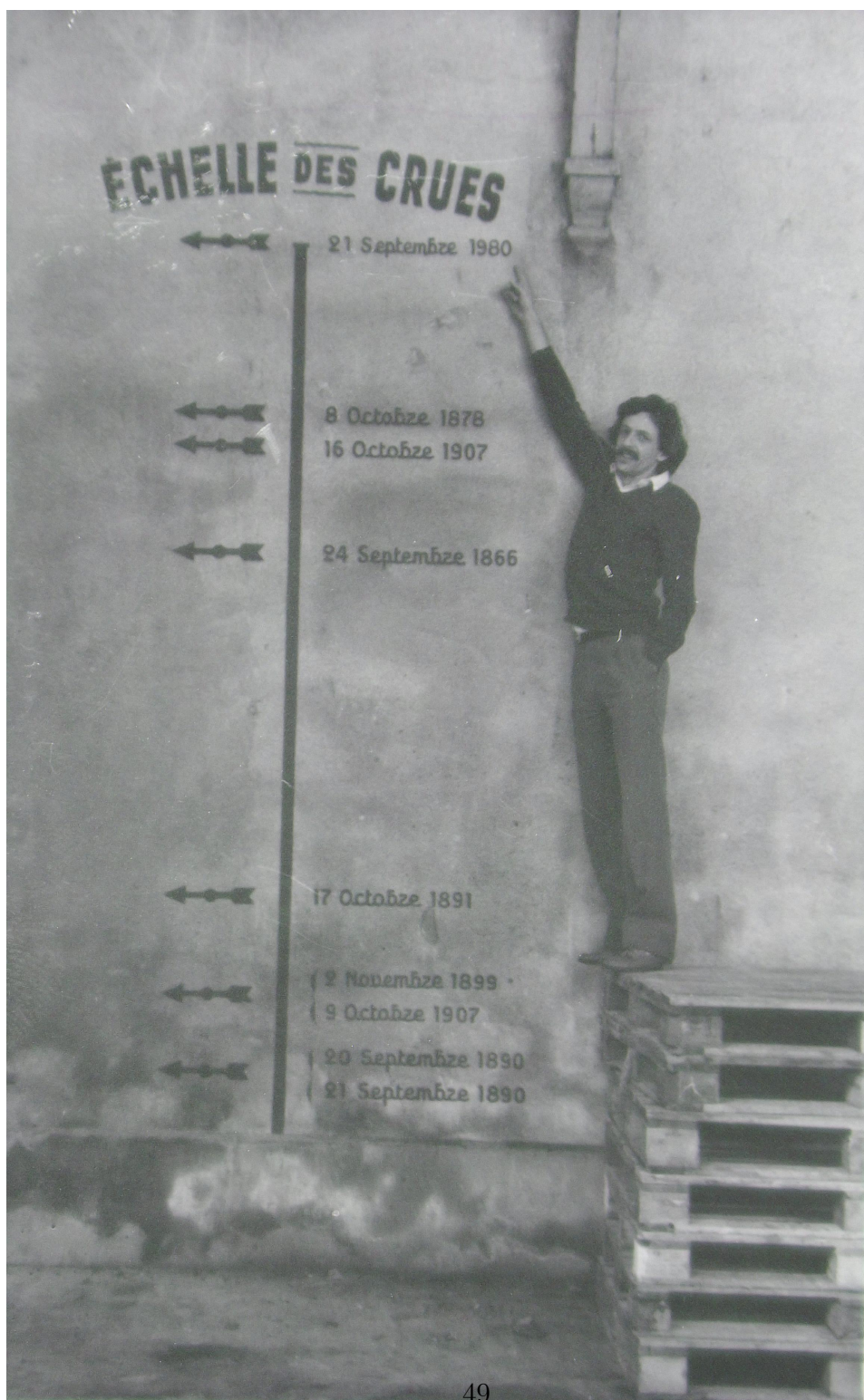


Figure 1: Flood marks on the Loire river at Puy-en-Velay (France).

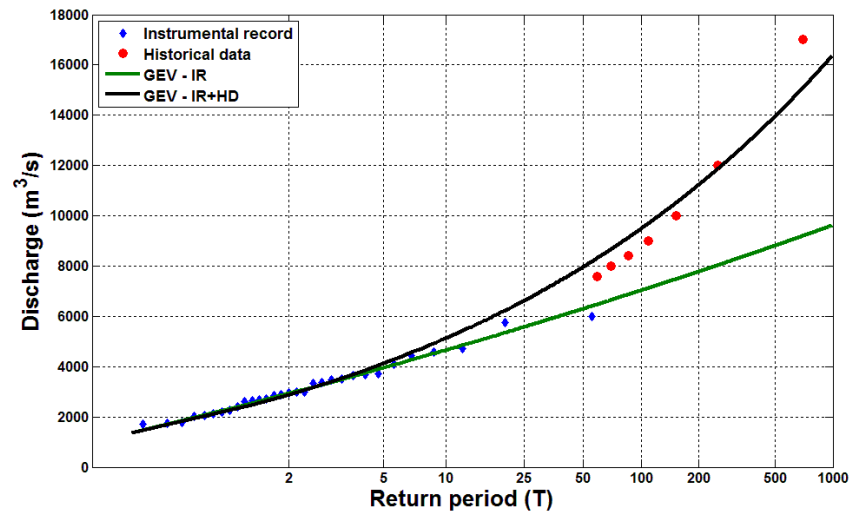


Figure 2: Improvement of the frequency curve estimation by the use of instrumental record (IR) and historical data (HD) available at the Tortosa gauging station in Spain.

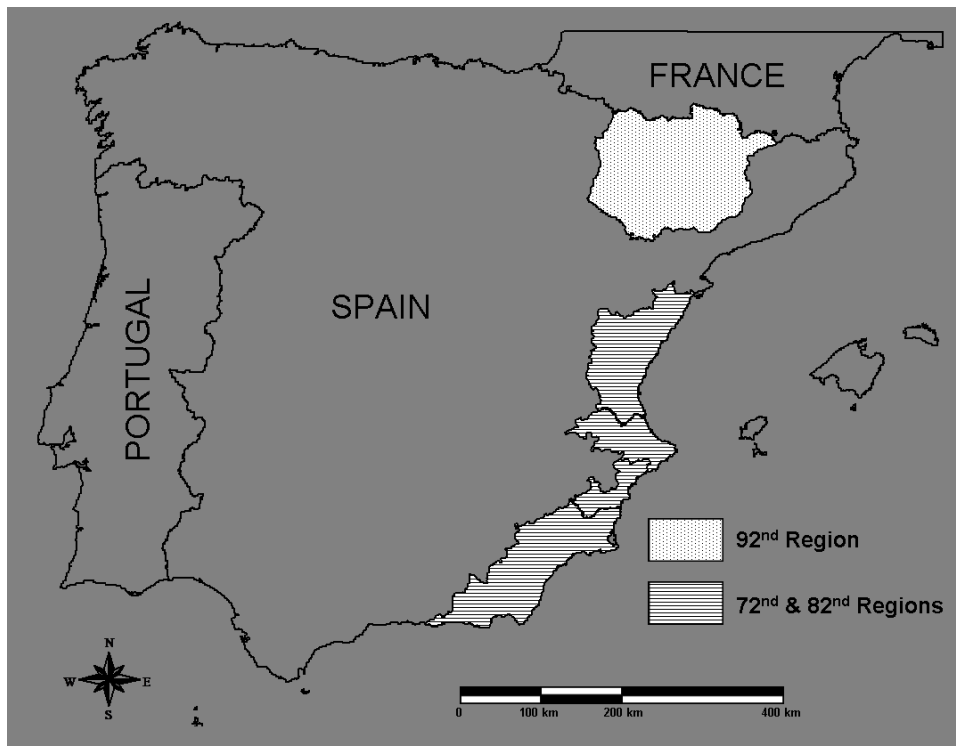


Figure 3: Location of regions in Spain where historical information was used for improving the estimation of the frequency curve.